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SURFACE IMPEDANCE OF HIGH T_C SUPERCONDUCTORS

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I discuss the various experiments which give information on the surface impedance $Z_s = R_s + jX_s$ of high temperature superconductors. The surface reactance X_s is related to the penetration depth λ and $X_s(T)$ is suggestive for singlet pairing. The surface resistance R_s is determined by the ac losses due to imperfections and due to thermally excited carriers, and experiments on high quality $YBa_2Cu_3O_7$ films indicate a superconducting gap which exceeds the BCS weak coupling limit. The various high frequency device applications are also briefly discussed.

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1. INTRODUCTION

The surface impedance Z_s is one of the parameters which reflects the electrodynamics of the superconducting state. At the same time it is perhaps the most important technical parameter which determines the application potential of the superconductors for high frequency passive components and devices.

The surface impedance is defined as[1]

$$Z_s = \frac{E_o}{\int_0^\infty j dx} \tag{1}$$

where E_o is the electric field of the surface, j the ac current in the sample and the x direction is perpendicular to the surface.

Z_s is, in terms of the complex conductivity $\sigma = \sigma_1 - i\sigma_2$, given by

$$Z_s = \left(\frac{\mu_o \omega}{\sigma_1 - i\sigma_2} \right)^{1/2} = R_s + iX_s \tag{2}$$

where μ_o is the permeability of free space, R_s and X_s are the surface resistance and surface reactance, and ω the measuring frequency.

The surface reactance is given, in the superconducting state well below T_c by

$$X_s(T) = \mu_o \omega \lambda(T) \tag{3}$$

with λ the penetration depth, and the measured $X_s(T)$ can be compared with various models of the superconducting state.

The surface resistance has been calculated in the local limit by

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Mattis and Bardeen,[2] and $R_s(T)$ is in good agreement with experiments conducted on classical superconductors. For the high temperature superconductors, the mean free path is comparable to the coherence length ξ, and consequently finite mean free path effects are important,[3] and have to be taken into account when experiments are compared with the various theories of the superconducting ground state.

2. EXPERIMENTAL TECHNIQUES

The majority of the experiments[4-8] are conducted by using resonant structures, with the superconducting material forming part of the structure. Both cavity endwall and cavity perturbation techniques have been utilized, they give somewhat different information on R_s and X_s. In all cases R_s and X_s is determined using a configuration where these parameters refer to electric currents flowing in the planes (if thin films are investigated). Alternatively, stripline and delay line configurations can be used with films either the central conductor or endplate of the resonator.

The various radio frequency and microwave techniques are usually applied to bulk or thin film samples, and depend on measuring relative small changes in the value of the surface impedance in the superconducting state compared with the normal state. The sample is normally placed in the magnetic field associated with a resonant circuit and the change in the resonance frequency f_o and quality factor Q is measured as a function of the temperature. The changes normally represent a small perturbation on the resonance, and can be linearly related to the changes in the surface impedance of the sample:

$$\Delta\left(\frac{1}{Q}\right) - 2j\left(\frac{\Delta\omega_o}{\omega_o}\right) = \gamma\Delta Z_s = \gamma\left(\Delta R_s + j\Delta X_s\right) . \qquad (4)$$

γ is a geometric factor associated with the dimensions of the resonator and the sample.

3. EXPERIMENTAL RESULTS

The temperature dependence of λ has been evaluated using both resonant cavity[7] and delay line[8] configurations, and the results are in broad agreement with experiments utilizing low field magnetization[9] and muon spin resonance[10] techniques. All suggest singlet pairing. The expected temperature dependence of λ is different for weak and strong coupling, but the available experiments can not convincingly determine whether strong coupling effects are important.

$R_s(T)$ measured on a ceramic, sputtered thin film and laser ablated film[1,4,5,11] is displayed in Fig. 1. One observes a finite residual resistance as $T \to 0$, and $R_s(T)$ depends also strongly on the film quality, with laser ablated films[11] -- the highest overall quality -- giving the lowest $R_s(T)$ values.

The large R_s for the majority of materials is due to a second phase[12] or due to grain boundaries which act like Josephson coupling between the grains.[13] In a simple model[13] of grain boundary effects on the surface impedance of thin films, the material is modeled as a network of superconducting grains coupled by Josephson junctions, which are described using the standard resistively shunted junction model with negligible capacitance. The parameters of the model are the junction J_cR product (J_c is the junction critical current and R the junction resistance) and the effective grain size a. The parameters which enter are, $L_G = \mu_0\lambda_{ab}^2$ the kinetic inductivity of the grain for current flow in the ab plane (penetration depth λ_{ab}), and, $L_J=\hbar/2eJ_c$ the unit areal inductance of the

junction.

For such a description of the grain boundary, the surface impedance is given by

$$Z_s = \omega\mu_0\lambda_{eff}\left[j + \frac{1}{2}\left(\frac{\lambda_j}{\lambda_{eff}}\right)^2 \frac{\hbar\omega}{2eJ_cR}\right] , \qquad (5)$$

with

$$\lambda_{eff} = \sqrt{\lambda_{ab}^2 + \lambda_j^2} \quad , \quad \lambda_J = \sqrt{\frac{\hbar}{a2eJ_c\mu_0}} \; . \qquad (6)$$

and λ_{ab} the penetration depth in the planes. The model accounts well[13] for the increased penetration depth and increased surface resistance of sputtered superconducting films.

For laser ablated films, grain boundary effects are not important, and $R_s(T)$[14] can be compared with the various theories[2,3] of the surface impedance. In Fig. 2 we display the experimental values (after correction for finite film thickness)[15] with a calculation based on the Mattis-Bardeen model,[2] and calculations with finite mean free path effects[3] with various gap values. The lower and upper set of experimental points have been obtained by employing two, different procedures for substracting the low temperature residual surface resistance. They represent the lower and upper limit of the true surface resistance R_s (T). It is evident that the experimental results lie below R_s(T) arrived at for a ealistic model, with $\ell/\pi\xi_0 = 1$ and $2\Delta = 3.5k_BT_c$ (corresponding to ξ_0 = 16A and ℓ = 50A, both parameters referring to the in-plane parameters). This suggests that Δ is larger than the weak coupling limit, and a value $2\Delta \sim 5k_BT_c$ appears

to describe our results well. Consequently, surface impedance studies suggest, that $YBa_2Cu_3O_7$ is in the strong coupling limit with Δ exceeding well the BCS value. Our results also convincingly rule out drastic deviations from a gap which opens up along the entire Fermi surface. We note, that the experimental configuration employed by us leads to ac current in the CuO_2 planes, and consequently, no information is gained on the ac losses for currents perpendicular to the planes.

4. APPLICATIONS

Due to the low ac loss, high temperature superconductors can be used in a variety of high frequency passive devices. In high quality $YBa_2Cu_3O_7$ and Tℓ-based[16] superconducting films R_s is significantly smaller than that of copper in the microwave spectral range. Consequently, various high frequency devices have been fabricated with performance characteristics superior to those fabricated using normal metals.

Examples include microwave resonators, delay lines and filters,[17]. These can be used also to study the electrodynamics of the superconducting state,[8,15] and to evaluate the temperature dependence of the surface resistance and penetration depth. While such devices will most probably be the first which will be commercially available, several issues have to be resolved before commercialization takes place. Among then substrate losses, power dependences, radiation and leakage problems[18] are the most prominent.

5. ACKNOWLEDGEMENTS

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CAPTIONS

Fig. 1. Surface resistance of a ceramic, sputtered thin film and laser ablated thin film of $YBa_2Cu_3O_7$. The full line is the Mattis-Bardeen expression of the surface resistance R_s. While R_N is different for different materials, in the Figure all are normalized to $R_N = 0.5\Omega$, corresponding to $\rho_N = 60\mu cm$, just above T_c.

Fig. 2. Surface resistance of laser-ablated $YBa_2Cu_3O_7$. The full lines are expressions, with and without mean free path corrections. with parameters ℓ/ξ_o and Δ given on the figure. The curve with $\ell/\pi\xi_o = o$ is the Mattis-Bardeen result.

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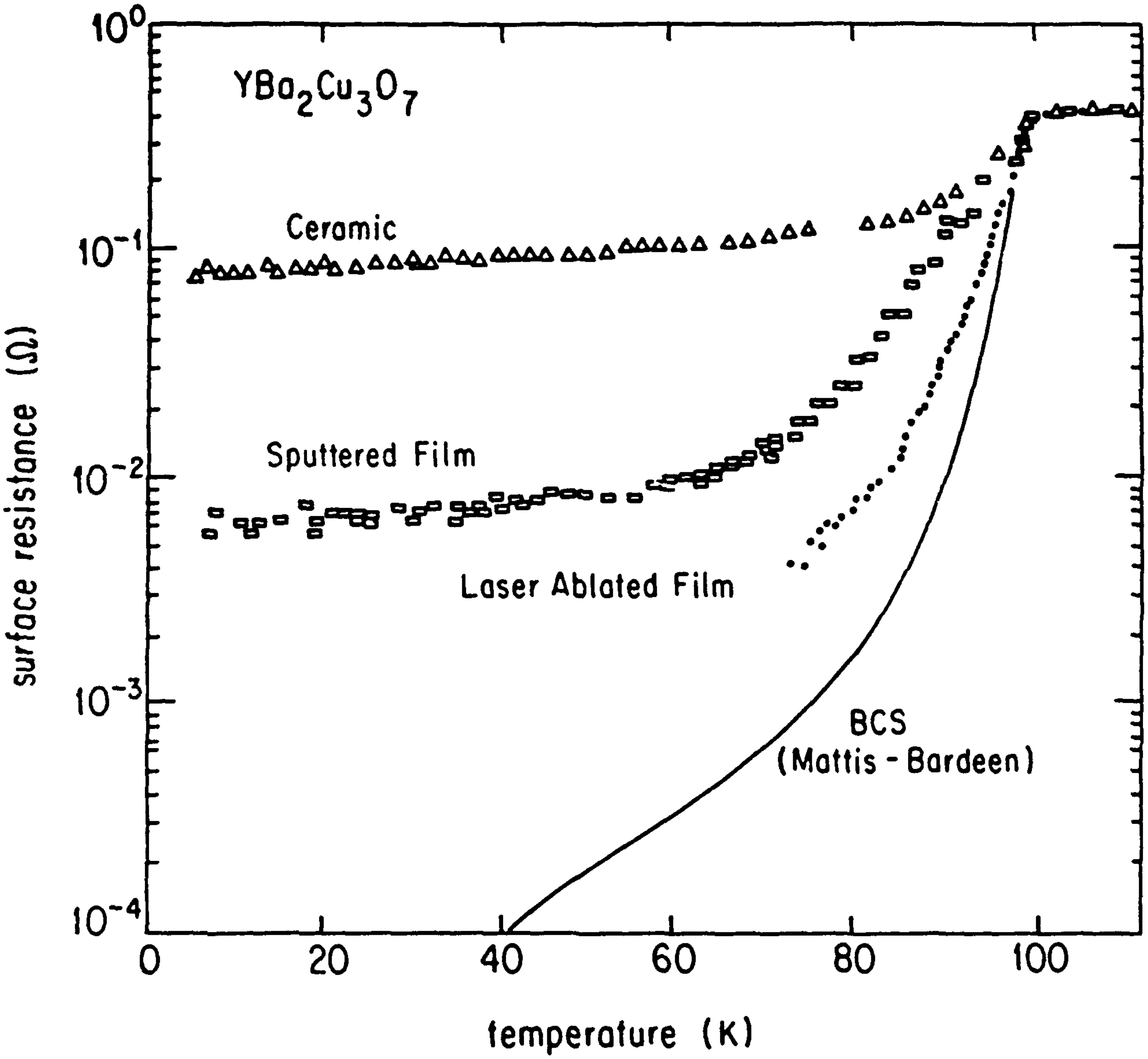
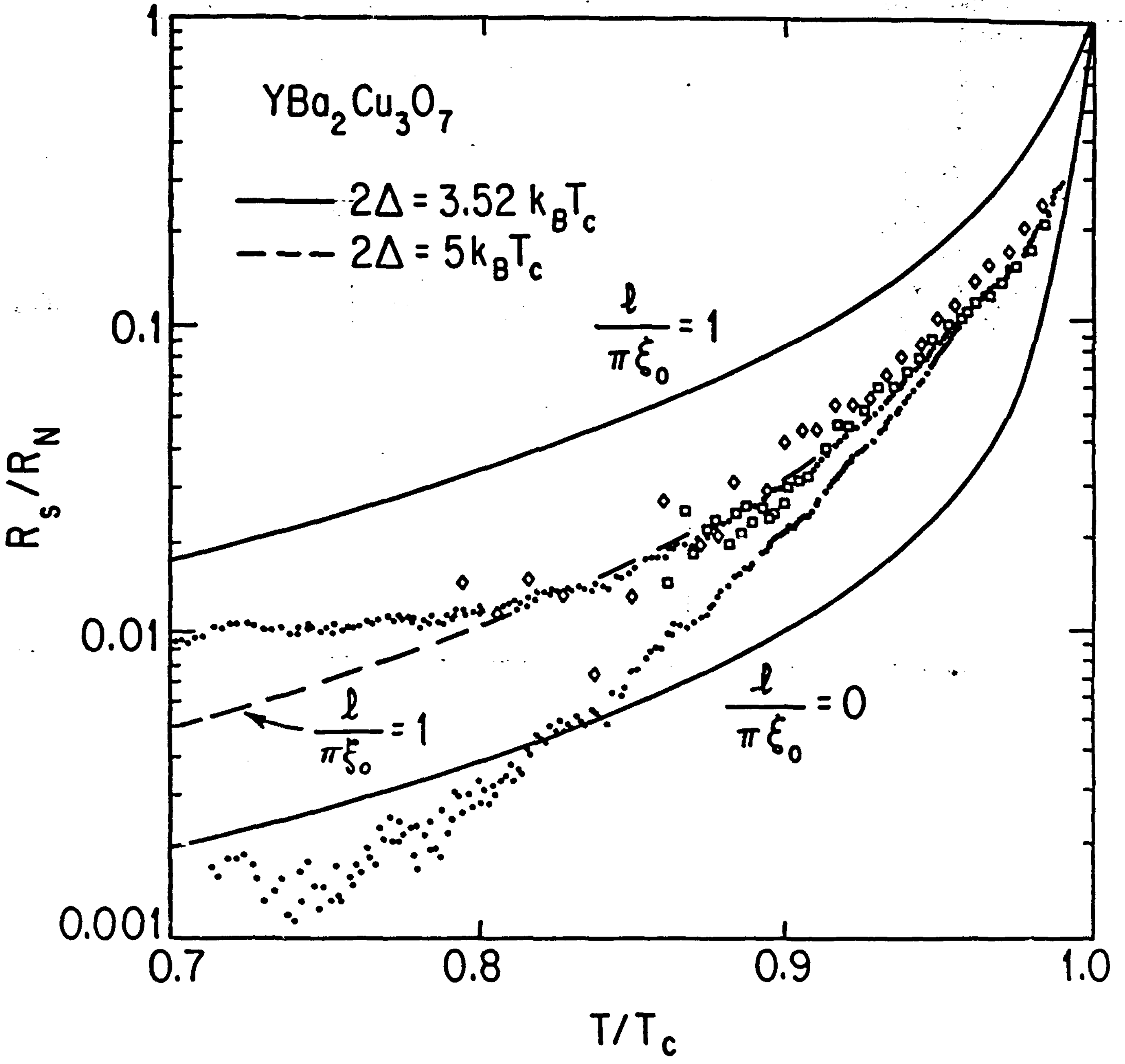


$YBa_2Cu_3O_7$
Ceramic
Sputtered Film
Laser Ablated Film
BCS
(Mattis - Bardeen)
surface resistance (Ω)
temperature (K)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100



$YBa_2Cu_3O_7$
$2\Delta = 3.52\ k_BT_c$
$2\Delta = 5k_BT_c$
$\frac{\ell}{\pi\xi_0} = 1$
$\frac{\ell}{\pi\xi_0} = 1$
$\frac{\ell}{\pi\xi_0} = 0$
R_s/R_N
T/T_c
1
0.1
0.01
0.001
0.7
0.8
0.9
1.0